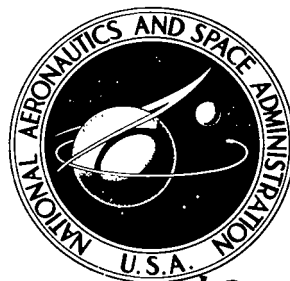


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ANALYSIS OF THE FLOW IN A 1-MJ ELECTRIC-ARC SHOCK TUNNEL

by John O. Reller, Jr., and N. M. Reddy

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NOTATION

a	speed of sound
A	constant in equation (21), $A = 6 \times 10^{20} \text{ cm}^3 \text{ }^\circ\text{K/mole sec}$; effective area of inviscid nozzle flow
c_b	coefficient of specific heat for Pyrex 7740
d	diameter
E	internal energy
E_c	capacitor bank energy
h_R^0	heat of dissociation per unit mass
H	total enthalpy
H_R	reference enthalpy (300 J/g)
j	0 for two-dimensional flow; 1 for axisymmetric flow
K_b	coefficient of conductivity of Pyrex 7740
Le	Lewis number
m	molecular weight
M_s	shock Mach number (U_s/a_1)
p	pressure
p_t	pitot pressure
Pr	Prandtl number
\dot{q}	convective heat-transfer rate
R	gas constant per unit mass of undissociated molecules
R_n	dimensionless velocity number defined in equation (1)
S	entropy
S_n	shock tube number defined in equation (2a)
T	absolute temperature
U	flow velocity relative to tube wall

U_s	shock velocity
U_3	limiting velocity, $2a_4/\gamma_4 - 1$
V	volume of the driver
Z	compressibility, $1 + \alpha$
α	atom concentration
α_p	temperature coefficient of resistance of platinum film
γ	ratio of specific heats
δ^*	boundary-layer displacement thickness
ϵ	density ratio across a normal shock wave, ρ_1/ρ_2
μ	dynamic viscosity
ρ	gas density
ρ_b	density of Pyrex 7740
η	efficiency of the driver
ψ	parameter involving γ , defined in equation (10)
θ	characteristic dissociation temperature; 113,260° K for nitrogen

Subscripts

0	reservoir condition at end of shock tube
1	quiescent test gas ahead of incident shock wave
2	test gas between incident shock wave and contact surface
3	driver gas behind incident contact surface
4	driver chamber conditions after arc discharge
e	edge of the boundary layer
eq	equilibrium boundary-layer model
fc	fully catalytic
fm	free molecule flow model
fr	frozen boundary-layer model

i	initial driver condition before arc discharge
nc	noncatalytic
T	tailored interface
∞	free-stream condition at exit of nozzle

Superscript

*	nozzle sonic throat
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ANALYSIS OF THE FLOW IN A 1-MJ ELECTRIC-ARC SHOCK TUNNEL

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SUMMARY

An investigation has been conducted in the Ames electric-arc-heated shock tunnel to evaluate the performance of the facility over a range of shock Mach numbers from 7 to 19. The efficiency of the arc-heated driver is deduced using a new form of the shock-tube equation. A theoretical and experimental analysis is made of the tailored-interface condition. The free-stream properties in the test section, with nitrogen as the test gas, are evaluated using a method based on stagnation-point heat-transfer measurements.

INTRODUCTION

The shock driven wind tunnel has played an important role in the study of hypervelocity aerodynamics, in part because of the wide range of flow velocities available and the relative ease with which the composition of the test stream can be varied. Relatively long duration test flows may be obtained with the tailored-interface mode of operation, as discussed in references 1 and 2. Heated hydrogen drivers (ref. 3) and combustion drivers (refs. 4, 5, 6) have been extensively used to produce tailored shock Mach numbers in the range of 6 to 9. However, higher shock Mach numbers are necessary to dissociate and ionize gases such as nitrogen and carbon monoxide, which are of interest in planetary entry studies. To achieve such conditions within the constraints imposed by the tailored mode of operation requires driver gas temperatures in excess of 2000° K. Arc-discharge heating (refs. 7 and 8) has been used successfully in this application; a wide range of driver temperatures is made available by varying driver loading pressure or discharge energy. This attractive scheme has been used for the Ames electric-arc shock tunnel (EAST), which has a capacitor storage system rated at 1 MJ.

In the present study, the characteristics of the heated driver and the tailored-interface operation of the shock tube (with nitrogen) have been considered, both theoretically and experimentally. The major emphasis, however, is on evaluating the properties of the highly expanded nitrogen stream in the test section. In this low-density environment, the more conventional methods of stream evaluation, which rely on probe measurements of static pressure, are inaccurate, largely because of substantial corrections for orifice and probe boundary-layer effects. Thus, in this study a number of quantities characterizing the flow in the EAST test section have been deduced using a new technique based on stagnation-point heating-rate measurements. Other flow properties were obtained from these measurements by application of the sudden-freeze concepts of reference 6. The results are compared with numerical solutions of nonequilibrium nozzle flow using the method of reference 9.

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THEORETICAL CONSIDERATIONS

The idealized performance of an electric-arc-heated driver and shock tube can be predicted easily for any driver gas or test gas mixture using the generalized form of the classical shock-tube equation presented in reference 10. This form of the shock-tube equation presents simple expressions for the tailored mode of operation and provides an easy method of calculating the actual efficiency of the electric-arc-heated driver. This information is the basis for estimating reservoir conditions at the nozzle inlet for an arbitrary test gas. These conditions in turn are input quantities for calculating the flow properties in the expansion nozzle and test section. The concepts of reference 10 are reviewed briefly and applied to the arc-heated driver; comparisons are made of predicted and realized reservoir conditions.

The Shock-Tube Equation

It is shown in reference 10 that by defining a dimensionless velocity

$$R_n \equiv \frac{U_2}{\hat{U}_3} \quad (1)$$

the classical shock-tube equation, relating particle velocity behind the incident shock wave to driver gas properties before diaphragm opening, can be reduced to a universal form given by

$$S_n = \frac{(1 - R_n)^{\gamma_4/(\gamma_4 - 1)}}{R_n} \quad (2a)$$

where

$$S_n = \frac{2\gamma_1}{\gamma_4 - 1} \frac{a_4/a_1}{\sqrt{\gamma_1 p_4/p_1}} = \frac{2\gamma_4}{\gamma_4 - 1} \sqrt{\frac{\rho_1/\rho_4}{\gamma_4}} \quad (2b)$$

and

$$R_n = \frac{(\gamma_4 - 1)(1 - \epsilon)M_s}{2(a_4/a_1)} \quad (2c)$$

In equations (2) the driver gas is assumed to be perfect, but no assumption as to the thermodynamic state of the driven gas is made. (Equations (2) are for a constant-area tube and represent the exact solution for perfect gases to within 3 percent at $M_s > 4$.)

In an electric-arc-heated facility, the driver gas is heated at constant volume and hence the initial density ρ_i is equal to the final density ρ_a after heating. Hence

$$\frac{\rho_1}{\rho_a} = \frac{\rho_1}{\rho_i} \quad (3)$$

Also

$$\frac{\rho_1}{\rho_i} = \frac{p_1}{p_i} \frac{m_1}{m_i} \quad (4)$$

since in general $T_1 = T_i$. With the use of equations (3) and (4), the shock-tube equation can be reduced to

$$S_n = \frac{2\gamma_4}{\gamma_4 - 1} \sqrt{\frac{(p_1/p_i)(m_1/m_i)}{\gamma_4}} = \frac{(1 - R_n)^{\gamma_4/(\gamma_4 - 1)}}{R_n} \quad (5)$$

Thus, the dimensionless shock-tube number S_n , for constant-volume heating of the driver gas, depends only on the initial pressures and molecular weights of the driver and driven gases. Equation (5) is convenient to use for estimates of shock-tube performance for any combination of gases; in graphical form, the variation of R_n with S_n is a single curve for a given γ_4 . The value of R_n that corresponds to a particular S_n is unique in the sense that it is independent of the thermodynamic state of the gas behind the shock wave. Having R_n , we use equation (2c) to relate M_s directly to a_4 and T_4 , the speed of sound and temperature in the heated driver gas. Obviously, if M_s is measured, then an effective T_4 can be determined.

Driver Efficiency

In an electric-arc-heated driver with constant volume heating of a perfect gas (ref. 11)

$$\frac{T_4}{T_1} = 1 + (\gamma_i - 1) \frac{\eta E_c}{V p_i} \quad (6)$$

and

$$\frac{a_4}{a_1} = \left(\frac{\gamma_4}{\gamma_i} \frac{m_1}{m_i} \frac{T_4}{T_1} \right)^{1/2} \quad (7)$$

These driver-heating equations can be combined with shock tube equations (2c) and (5) to obtain the efficiency of the driver. With a_4/a_1 derived from measured M_s , and equation (2c) with the appropriate value of R_n , equation (6) will yield η . In the present study, η was based on M_s measured at the downstream end of the shock tube, and as such includes losses associated with shock-wave attenuation. It could be reasoned that this approach results in a lower estimated driver efficiency, because it does not account for viscous losses in the shock tube; however, the result does give an estimate of overall driver effectiveness. The efficiencies so determined are discussed in a later section on driver performance.

Tailored-Interface Operation

At the downstream end of the shock tube a reservoir of heated gas is produced by reflection of the incident shock wave from the end wall. An optimum condition exists if the downstream wave, resulting from the interaction of the reflected shock wave with the contact surface, is a Mach wave. When this occurs, the contact surface (interface) is said to be "tailored." Since this secondary reflection is vanishingly weak, the reservoir conditions remain steady for a longer period — in theory, until the arrival of the main driver expansion. For tailored operation a matching condition can be derived for the perfect driver and driven gas case, as shown in reference 12; for example,

$$\left[\frac{E_3}{E_2} \right]_T \approx \frac{\gamma_4 + 1}{\gamma_4 - 1} \frac{\gamma_1 - 1}{\gamma_1 + 1} \quad M_s^2 \gg 1 \quad (8)$$

The dimensionless number R_n can be used to write the ratio of internal energies, following reference 10, as

$$\frac{E_3}{E_2} = \frac{\gamma_4 - 1}{2\gamma_4} \left(\frac{1 - R_n}{R_n} \right)^2 \quad (9)$$

From equations (8) and (9) the tailored value of R_n is

$$[R_n]_T = \frac{1}{1 + \psi^{1/2}} \quad (10)$$

where

$$\psi = \frac{\gamma_4 + 1}{\gamma_4 - 1} \frac{2\gamma_4}{\gamma_4 - 1} \frac{\gamma_1 - 1}{\gamma_1 + 1}$$

Then equation (5) reduces to

$$[S_n]_T = \frac{2\gamma_4}{\gamma_4 - 1} \left[\frac{m_1/m_i}{\gamma_4(p_i/p_1)} \right]^{1/2} = \frac{\psi^{\gamma_4/2(\gamma_4-1)}}{(1 + \psi^{1/2})^{1/(\gamma_4-1)}} \quad (11)$$

Equations (10) and (11) represent the tailoring conditions for thermodynamically perfect gases. From equation (11) it is evident that for a given combination of driver and driven gases, the ideal loading pressure ratio p_i/p_1 required for tailored operation is a constant, regardless of the quantity of energy discharged into the driver gas. The loading pressure ratios for tailored operation with the different gas combinations used in these experiments are given in table 1.

The tailored shock Mach number is given by

$$[M_s]_T = \frac{2(a_4/a_1)}{(\gamma_4 - 1)(1 - \epsilon)} [R_n]_T \quad (12)$$

Using equations (6) and (7) to obtain a_4/a_1 , equation (12) can be written as

$$[M_s]_T = [R_n]_T \frac{2}{(\gamma_4 - 1)(1 - \epsilon)} \left\{ \frac{\gamma_4}{\gamma_1} \frac{m_1}{m_i} \left[1 + (\gamma_4 - 1) \frac{\eta E_c}{V p_i} \right] \right\}^{1/2} \quad (13)$$

where $\epsilon \approx (\gamma_1 - 1)/(\gamma_1 + 1)$ is the perfect gas value of the density ratio across a normal shock wave for $M_s \gg 1$, and $[R_n]_T$ is the constant given by equation (10). The tailored shock Mach number $[M_s]_T$ depends on the initial loading pressure p_i , the driver volume V , the stored capacitor energy E_c , and the choice of gases. A typical variation of $[M_s]_T$ with p_1 , with He driving N_2 , is given in figure 1, for $E_c = 10^6$ J and $V = 0.0209$ m³ (Ames 2.90 m arc-heated driver). As shown, this result from equation (13) compares favorably with a similar result from reference 2 where, for the same He- N_2 combination, nitrogen is treated as a real gas.

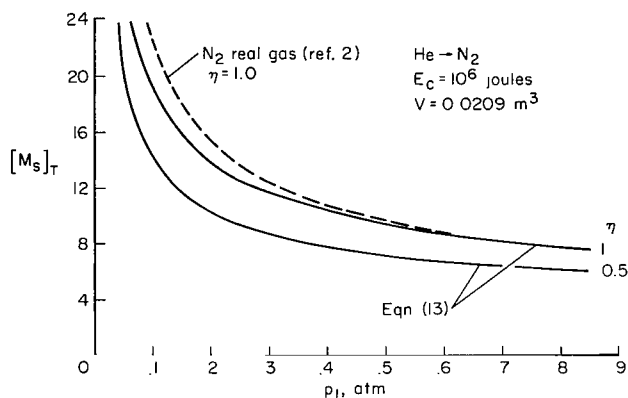


Figure 1.— Variation of tailored-shock Mach number with shock-tube loading pressure.

The preceding analysis indicates that if the appropriate ratio of p_i to p_1 is chosen the contact surface will be tailored at all shock Mach numbers. With the assumption of ideal shock-tube theory with thermodynamically perfect working gases inherent to this analysis, each tailored shock Mach number has a unique ratio of temperatures across the contact surface (T_3/T_2). In practice, this is not the case, however, because the temperature T_3 is influenced by real-gas effects, viscous losses, heat transfer to the wall, and nonuniform distribution of energy within the driver chamber. The temperature T_2 is affected by similar viscous and heating losses, real-gas effects, diaphragm opening, etc. Thus, these nonideal effects make it

impossible to predict from ideal theory the ratio of pressures that will give a tailored condition. However, a near-tailored reservoir can be obtained by adjusting p_i and p_1 , as discussed later.

Test Section Flow

This section considers methods of evaluating flow properties in the high-velocity test stream issuing from a steady reservoir of quiescent, shock-heated gas. It is assumed that the reservoir gas is in equilibrium, with respect to both vibrational and chemical energies. In reference 13 a method is described for determining the Reynolds number, viscosity, and atom concentration in a hypervelocity nozzle from the measurement of stagnation-point heat-transfer rates to three probes placed side by side (the three-probe method). The physical nose dimensions of the probes should be chosen so that one probe measures the heating rate \dot{q}_{eq} in the presence of an equilibrium (chemical) boundary layer, the second \dot{q}_{fr} in a frozen shock layer, and the third \dot{q}_{fm} in the free-molecule flow regime. With a pitot-pressure measurement, in addition to these three heating rates, the following relationships can be used. (The derivation of these equations and the probe design considerations are given in reference 13. The present results are subject, of course, to the assumptions of the reference analysis.) The shock-layer Reynolds number is

$$(Re)_e \equiv \frac{\rho_\infty U_\infty d_{fr}}{2\mu_e} = C^2 \left(\frac{\dot{q}_{fm}}{\dot{q}_{fr}} \right)^2 \quad (14)$$

where

$$C = 0.64(j+1)^{1/2} Pr^{-0.6} \epsilon^{-0.25}$$

The ratio of dissociation to total enthalpy is

$$\frac{\alpha_\infty h_R^0}{H_\infty} = \frac{\dot{q}_{eq} d_{eq}^{1/2} - \dot{q}_{fr} d_{fr}^{1/2}}{\dot{q}_{eq} d_{eq}^{1/2} + (Le^{0.52} - 1) \dot{q}_{fr} d_{fr}^{1/2}} \quad (15)$$

In equation (15) the two heat-transfer probes are assumed to be geometrically similar. Using the approximations

$$p_t \approx \rho_\infty U_\infty^2 \quad \text{and} \quad H_\infty \approx \frac{1}{2} U_\infty^2 + h_R^o \alpha_\infty$$

one obtains

$$U_\infty = \frac{2\dot{q}_{fm}}{p_t} \quad (16)$$

$$\rho_\infty = \frac{p_t^3}{4\dot{q}_{fm}^2} \quad (17)$$

$$\mu_e = \frac{1}{4} \frac{d_{fr}}{C^2} \frac{p_t^2 \dot{q}_{fr}^2}{\dot{q}_{fm}^3} \quad (18)$$

$$H_\infty = \frac{U_\infty^2}{2Le^{0.52}} \left[\frac{\dot{q}_{eq} d_{eq}^{1/2}}{\dot{q}_{fr} d_{fr}^{1/2}} + (Le^{0.52} - 1) \right] \quad (19)$$

$$\alpha_\infty = \frac{U_\infty^2}{2h_R^o Le^{0.52}} \left(\frac{\dot{q}_{eq} d_{eq}^{1/2}}{\dot{q}_{fr} d_{fr}^{1/2}} - 1 \right) \quad (20)$$

All the flow properties in the preceding equations are expressed in terms of the measured quantities, stagnation heating rate and pitot pressure. The unknowns are the two transport properties, Lewis and Prandtl numbers, and the shock density ratio ϵ , which must come from another source. Fortunately, they are relatively insensitive to test conditions and can be matched by an iterative solution if desired. An examination of equations (14) through (20) shows that the derived values of free-stream velocity U_∞ , density ρ_∞ , shock-layer viscosity μ_e , and Reynolds number $[Re]_e$ require only two of the three measured heating rates, namely \dot{q}_{fr} and \dot{q}_{fm} ; and that the free-stream Mach number M_∞ and Reynolds number Re_∞ cannot be obtained by this method, since the static temperature of the stream is not directly available. However, these latter properties can be derived from the present measurements by an adaptation of the sudden-freeze method of reference 6, as will be shown later. To assess the validity of this combined approach, a comparison will be made between the stream densities from the three-probe and the sudden-freeze methods, while U_∞ from equation (16) will be compared to the stream velocity obtained by a completely independent analysis.

EXPERIMENTS

In this section the methods discussed for determining driver efficiency, tailored-interface conditions, and flow properties are applied to the EAST facility.

The Test Facility

An electric-arc driver and energy storage system has been developed for shock-tunnel application, with provision for driver lengths up to 3 m. Such driver lengths are required to match the reservoir time requirements for tailored-interface operation (ref. 2). The energy for the arc is supplied by a 1250- μ F capacitor bank capable of storing 1 million joules when charged to a maximum of 40 kV. The arc is contained within a 10.2-cm-diam insulated chamber and is initiated by a tungsten wire. Details of the operating characteristics for the driver system are given in reference 14. (Dannenberg and Silva have developed methods to improve driver performance and range of operation; these are described in a forthcoming publication.) For the present experiments, driver lengths of 1.37 and 2.90 m were used. The energy per unit volume E_C/V was kept the same for both lengths (about 42 J/cm³) with capacitor bank voltages of 28 and 40 kV, respectively. The driver is coupled to a 10.2-cm-diam, 11.3-m-long shock tube, which discharges into a 10° half angle, conical supersonic nozzle. A 76-cm, hexagonal test section and a vacuum tank are located downstream of the nozzle. Figure 2 is a schematic diagram of the facility. Interchangeable sonic

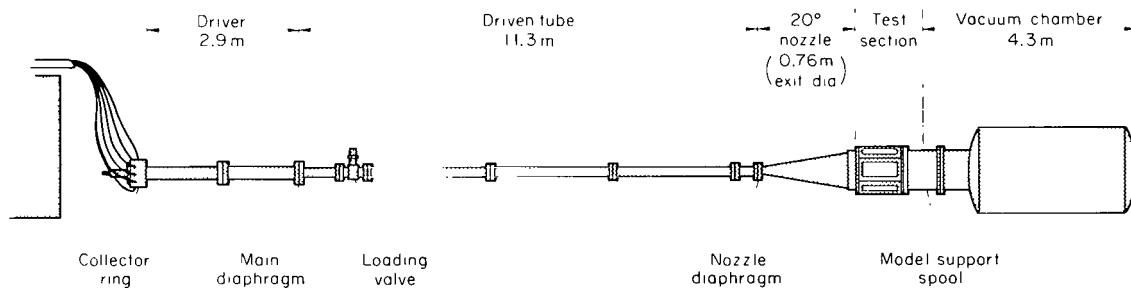


Figure 2.— Schematic of Ames electric-arc shock tunnel.

throats can be inserted at the nozzle entrance to permit operation at different flow Mach numbers. The shock wave arrival was monitored at six stations in the shock tube using the ion-probe system described in reference 15. Shock Mach number was calculated from the measured velocity and the initial gas temperature in the tube. The initial pressure p_1 was measured with a precision dial gage at the gas loading station, and the reservoir pressure p_0 with a piezoelectric transducer located in a sidewall port at 0.64 cm from the endwall. Test gas impurities were estimated to be less than 1.0×10^{-3} of the total sample.

Driver Performance

Driver efficiencies, determined by the method described earlier, are shown in figure 3 for the range of loading pressures p_i of the present tests. Equivalent driver temperatures computed from equation (6) are included for reference. Experimentally determined efficiencies were based on the shock velocity measured near the end of the 11.3-m tube and thus include the energy loss associated with shock attenuation. At values of p_i from 10 to 15 atm, the He and N₂ drivers operate with an overall efficiency of about 50 percent. With the addition of argon to the driver gas, which lowers M_s because of the decrease in a_4 , the driver efficiency varied substantially from run to run. In all cases η was better than for helium alone, but the wide variation from 0.60 to over 1.0 is a surprising result. It is inferred that the arc-discharge and heat-transfer processes in the driver chamber are variable, perhaps because of local variations in gas mixture ratio. Since the basis of comparison is a

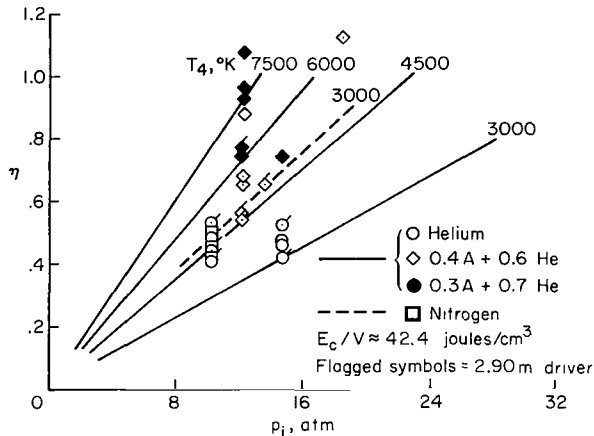


Figure 3.— Overall driver efficiency and equivalent temperature; 1.37- and 2.90-m drivers.

Reservoir Conditions

In an earlier section, the ratios of initial driver-to-driven-tube pressures were predicted for tailored interface operation with ideal gases. For a given combination of gases the ratio is a fixed constant, although absolute values can be changed to vary M_S . As part of the experiment, an effort was made to validate this prediction, using the pressure ratios listed in table 1. It was quickly found that nonideal effects resulted in undertailored conditions — an undertailored condition is a mismatch of internal energy at the contact surface such that $E_3 > E_2$, causing a downstream expansion wave to emerge from the reflected shock-contact surface interaction. This situation can be corrected by lowering p_1 , while keeping a_4/a_1 constant, or by decreasing a_4/a_1 with p_1 constant, until the tailored condition is achieved. To obtain reasonably constant reservoir pressure histories with nitrogen as the test gas, it was necessary to increase the ratios p_i/p_1 by about an order of magnitude by a reduction in p_1 . This is not surprising since the shock Mach numbers attained in most high-energy shock tubes are below ideal predictions at the initial pressures considered here. The observed departure from the ideal pressure ratio in this experiment is attributed to an elevated temperature behind the contact surface T_3 , partly due to deceleration of the incident shock wave and partly to a timewise variation of total temperature in the gas issuing from the driver. These nonideal effects are the subject of a separate investigation.

Figure 4 shows representative reservoir pressure histories for the M_S range and the driver gases used. Figure 4(a) is a record of a somewhat undertailored condition at $M_S = 18.5$, which has a fairly constant pressure after the arrival of the expansion wave from the contact surface. This pressure level corresponds to an enthalpy in the test gas of about 40 kJ/g, considerably above that obtainable in combustion or heated hydrogen driven facilities. The tailored condition would occur at a slightly lower p_1 for $M_S > 18.5$. Figures 4(b) and 4(c) show slightly overtailored conditions for which weak compression waves augment the reflected-shock pressure.

An independent check of the reservoir gas quality was obtained by monitoring the radiant emission of the shock-heated nitrogen, using a photodiode detector with S-1 response. The reservoir gas was observed through a sidewall window masked by a 0.025-cm vertical slit for collimation; signals were recorded on an oscilloscope. Although the detector was not calibrated for absolute intensity, care was taken to operate in the linear response range. Typical results (fig. 5) show that

uniformly heated driver gas, it is obvious that nonideal effects can be strong enough to create shock waves that exceed the ideal velocity. It should be noted, moreover, that $\eta > 1.0$ has been reported in reference 8 for pure helium drivers at relatively low temperatures T_4 . Here again one logical explanation is nonuniform driver heating. Further investigation of this behavior is warranted since it will influence interface temperatures T_2 and T_3 , which determine tailored operation.

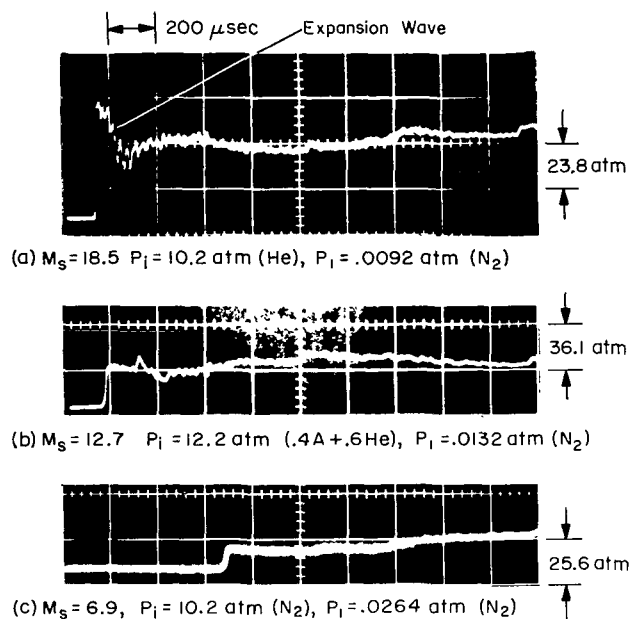


Figure 4.— Reservoir pressure histories at near-tailored conditions.

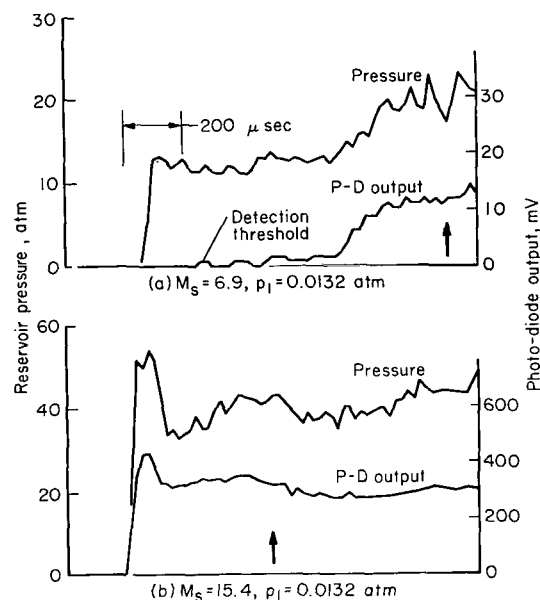


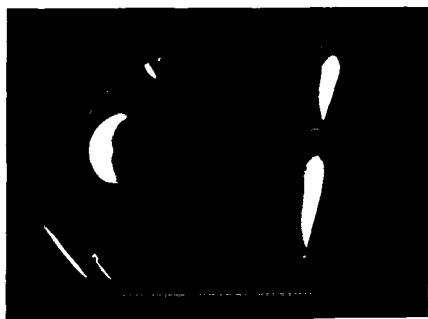
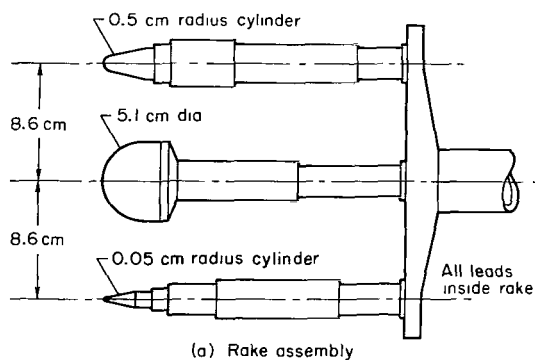
Figure 5.— Pressure and radiation histories in the reservoir, 0.64 cm from end wall.

the radiation from the reservoir varies with the pressure for at least 1 msec at $M_S = 6.9$, and for about 0.5 msec at $M_S = 15.4$. In a qualitative sense, this finding indicates that no large dilution of the test gas occurs in these times.

Test Section Measurements

As the shock-heated, partly dissociated nitrogen in the reservoir expands into and beyond the throat of the supersonic nozzle, a point is reached where the recombination and vibrational relaxation become rate limited and can no longer follow the rapid change of temperature. When this occurs, the flow changes over a relatively short distance from local equilibrium to a state in which one or both of the two forms of internal energy (vibration and dissociation) are nearly invariant. In effect, the flow "freezes" at an intermediate level of dissociation and vibrational energy distribution, and remains essentially in this state as it sweeps through the test section. Consequently, the properties of the test stream differ from those in an equilibrium expansion; the temperature, pressure, and velocity are lower while the Mach number is higher. The calibration method must determine these differences, measure the dissociation level, and if possible, the vibrational energy defect of the flow.

The three-probe rake— The flow quantities in the test section were evaluated, in part, using the three-probe method described earlier. The probes were mounted together on a single rake for simultaneous measurements of stagnation-point heating rates in the equilibrium boundary layer, frozen shock layer, and free-molecule flow regimes. The nose diameters were $d_{eq} = 5.1$ cm, $d_{fr} = 1.0$ cm, and $d_{fm} = 0.10$ cm; the largest probe was hemispherical and the two smaller probes were cylindrical in shape. Figure 6 shows a diagram and a photograph of the three-probe rake immersed in the test flow. For the present range of conditions, the computations presented in reference 13 show that a cylindrical probe of 0.10 cm diam is sufficiently small to obtain



(b) Rake in test stream

Figure 6.— Three-probe heat-transfer rake.

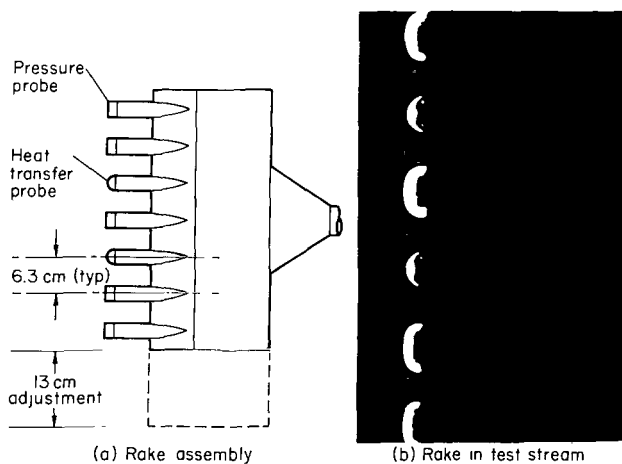
The sensing elements on the three probes were thin film platinum gages. To avoid shorting due to shock-layer ionization, all the gages were coated with a $1\text{-}\mu$ -thick layer of silicon monoxide by a vacuum evaporation technique. (The response time of a $1\text{-}\mu$ glass layer is about $50\text{ }\mu\text{sec}$ for 5 percent accuracy.) The backing material used was Pyrex 7740, which has the following properties: $(K_b \rho_b c_b)^{1/2} = 0.153\text{ J cm}^{-2} \text{ }^\circ\text{K}^{-1} \text{sec}^{-1/2}$ and $\alpha_p = 2.18 \times 10^{-3} \text{ } \Omega / \Omega \text{ }^\circ\text{K}$. The heat-transfer rates were determined directly with the use of analog

free-molecule flow at the stagnation point. On the basis of estimates and experimental results presented in reference 16, a cylindrical probe of 1.0-cm diam should result in frozen shock-layer conditions.

Estimates of the probe size for equilibrium boundary-layer flow in the stagnation region were based on the theory of reference 17. Although the reference analysis is specifically for air, it was assumed that the functional dependence of gas-phase reactions on local conditions would be similar for pure nitrogen. The resulting estimates of probe size, in the limit of a fully equilibrium boundary layer, exceeded the physical dimensions of the facility for many of the expected test conditions. Therefore, it was decided to relax the requirement of full equilibrium, retain the concept of three simultaneous measurements, and resolve the defect in heating rate by analytical means. A 5.1-cm-diam hemisphere was used for this measurement; for convenience, this probe will be referred to as the equilibrium heat-transfer probe.

The methods of reference 16 were followed closely in the design and construction of both the gages and the analog networks.

The survey rake— During test core surveys, other heating rates were measured on hemispherical models 2.5 cm in diam mounted on a rake spanning the test region (fig. 7). These models were copper shells, 0.013 cm thick, instrumented with 40 gage chromel-constantan thermocouples formed by soldering the individual wires of each pair into two closely spaced holes at the stagnation point. All the heat-transfer data were recorded by a high-speed data acquisition system (ref. 18), which provides digital information at the rate of one reading



(a) Rake assembly

(b) Rake in test stream

Figure 7.— Pressure and heat-transfer survey rake.

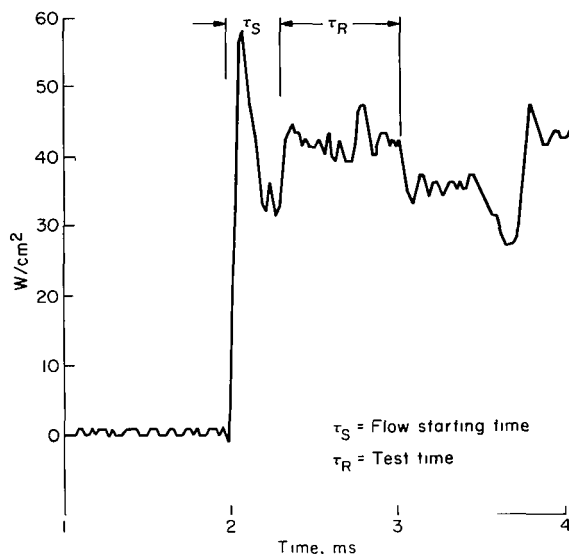


Figure 8.— Rate of heat transfer to the equilibrium boundary-layer probe ($M_S = 12.4$, $p_i = 0.0132$ atm).

heat-sink baffle to shield the active element (a pretensioned Invar diaphragm, 0.0013 cm thick) from heating effects.

The heat-transfer rates and the corresponding pitot pressures were measured for a wide range of shock Mach numbers (hence reservoir enthalpies) with nitrogen as the test gas. The driver gases were nitrogen, pure helium, and helium diluted with different amounts of argon; for each case the ratio of initial driver pressure to driven tube pressure p_i/p_1 was adjusted until a near-tailored condition was achieved. The three-probe rake was mounted in the horizontal center plane at the exit of a conical supersonic nozzle with a 0.32-cm-diam throat. The pressure and heat-transfer survey rake was mounted vertically in the same nozzle, at the same axial station, and offset to position pitot probes at the same radial distance as the outer models on the three-probe rake. Throat sizes of 0.32 and 1.27 cm were used with this rake. For the present range of experiments, the corrections to measured pitot pressures for rarefaction effects were estimated by the method of reference 19 and found to be less than 2 percent. The flow starting time in the nozzle (as in ref. 20, the time required to establish uniform flow after arrival of initial disturbance) is estimated from probe response to be between 150 to 300 μsec , and in general, varies inversely with M_S .

DISCUSSION

The data are summarized in table 2; the measured heating rates, pressures, and test times are grouped into two sets according to the instruments used. Test 1 refers to the runs made with the three-probe heat-transfer rake, using thin-film detectors. Test 2 results are from the survey rake that used thin-wall calorimeters to measure heat-transfer rates and variable capacitance transducers for pressure.

Analysis of the heat-transfer data from three-probe rake (test 1) gave inconsistent results over the range of test conditions. To isolate the cause of this erratic behavior, test 2 repeated several runs

every 2 μsec . The data were punched on a paper tape and processed on an IBM 7094 computer. A sample of the machine-plotted heat-transfer data is shown in figure 8.

Pitot pressures were measured, in repeat runs at each test condition, with a piezoelectric pressure transducer (Kistler, model 701A). These measurements were obtained with both a flush mounting (gage face exposed to the flow) and a recessed mounting arrangement. In both cases the gage face was coated with a very thin layer of silicone rubber to reduce the heating effects. (Reservoir pressures were measured with similar transducers (Kistler, model 601H).) Pitot pressures were also measured during test core surveys with an adjustable rake, which contained as many as seven variable-capacitance pressure transducers. These gages were mounted behind a

at identical starting conditions and extended the scope to include a larger nozzle throat size, $d^* = 1.27$ cm. Furthermore, as a check on the measuring techniques of test 1, a different type of heat-transfer sensor and pressure transducer were used. These were mounted in the survey rake that spanned the test region. The results of test 2 showed that the inviscid test core was smaller than predicted at the higher reservoir enthalpies. This result can be seen in table 2 where, for test 1, columns 7 and 10 indicate when the pitot pressure at the off-centerline location of the frozen-flow and free-molecule probes was lower than centerline pitot pressure. Column 13 of table 2 lists the time interval of useful data for each run, while column 14 gives an estimate of the duration of test gas flow based on reservoir radiation and test section heating rate measurements. In general, the longer flow times of column 14 could not be fully utilized because of pressure disturbances in the reservoir.

Nozzle Test Core

Rake surveys of the nozzle flow at the exit station, using the 0.32-cm-diam throat, showed that inviscid test cores varied in diameter from about 23 to 10 cm as the total enthalpy was increased from 8 to 40 kJ/g. Pressures were relatively constant across the core area and repeatable from run to run. At $H_\infty > 27$ kJ/g, the stream core size decreased to the point where the outer two probes on the heat-transfer rake (located 8.4 cm from the centerline) were in the outer edge of the nozzle wall boundary layer. For these conditions, the frozen-flow probe data were discarded, but the free-molecule probe results were assumed to represent a velocity close to the inviscid core value, since in the outer edge of a hypersonic boundary layer the density decreases much more rapidly than the velocity. For example, for the first run listed in table 2 the local pitot pressure was about 0.7 the centerline value; the corresponding defect in velocity is estimated to be less than 1 percent, while the local density decrease is nearly 30 percent. The corresponding local Mach number is only about 15 percent lower, so that the free-molecule probe should remain within the appropriate flow regime.

With a nozzle throat diameter of 1.27 cm, the measured test core diameter was greater than 40 cm over the entire range of reservoir conditions.

Total Enthalpy

As shown in table 2, the stagnation region boundary layer on the largest probe, as expected, did not come to chemical equilibrium. Therefore, it was not possible to compute the stream total enthalpy directly using equation (19). An alternate method was devised for indirect verification of the enthalpy, using the measured \dot{q}_{fm} and \dot{q}_{fr} along with an H_o derived from reflected shock conditions. The first step in this approach was to determine the chemical state of the shock layer by comparing the product of the rate of nitrogen dissociation and the flow residence time to the limiting value of equilibrium dissociation. The dissociation rate was estimated using the characteristic equation, as given for example in reference 21, which describes a diatomic gas with a binary collision mechanism

$$\frac{d\alpha}{dt} = (1 - \alpha) \frac{AP}{RT^{1+\omega}} e^{-\theta/T} \quad (21)$$

where $\omega = 1.5$ is half the number of degrees of freedom contributing energy during a collision and A is a constant determined by experiment for a particular gas. In the present case $d\alpha/dt$ was maximized by using the ideal gas ($\alpha = 0$) temperature just behind the shock wave.

Residence time was estimated from shock detachment distance and average local velocity. The uniform result was that even for this *maximum* dissociation rate the residence time was so short that the inviscid shock layer was effectively frozen at the stream composition (on the largest model) for all test conditions. Similarly, for the stagnation region boundary layer, a recombination rate parameter (the ratio of atom diffusion time across the boundary layer to characteristic atom lifetime)

$$C_1 = \frac{1.6 \times 10^{11} p d}{2 T^4 Z^{1/2}} \quad (22)$$

was used after the manner of reference 22, with pressure in atomspheres and nose diameter in centimeters. Values of C_1 varied from 10^{-6} to 10^{-8} over the test range and indicate atom lifetimes much in excess of transit time. Thus, the boundary layer in the stagnation region of the 5.1-cm probe is frozen to atom recombination for all test conditions.

With the chemical composition of the probe shock layer thus defined (frozen at stream composition) and assuming that reservoir enthalpy can be evaluated from the measured reservoir pressure at the entropy level associated with the reflected shock wave, the second step is to compute the convective heat transfer to a noncatalytic (glass covered) surface for several assumed values of α_∞ . When the expression for a frozen free stream and frozen shock layer is used (ref. 22),

$$\dot{q}_{nc} = \dot{q}_{fc} \left(1 - \frac{\alpha_\infty h_R^o}{H_o} \right) \quad (23)$$

where the heating rate to a fully catalytic surface \dot{q}_{fc} is essentially the same as that for an equilibrium boundary layer \dot{q}_{eq} . As suggested in reference 22, this latter value can be closely approximated for nitrogen by

$$\dot{q}_{eq} = 78.8 \left(\frac{2p_t}{d} \right)^{1/2} \left(\frac{\bar{U}_\infty}{10,000} \right)^{2.03} \left(1 - \frac{H_R}{H_\infty} \right) \quad (24)$$

where $\bar{U}_\infty \equiv (2H_\infty)^{1/2}$, the flow velocity for an equilibrium expansion; that is, \bar{U}_∞ includes the dissociation energy. The resulting values of \dot{q}_{nc} were interpolated to match the measured heating rate on the 5.1-cm probe, which yields α_∞ and the corresponding stream velocity U_∞ .

Alternately, U_∞ can be computed from equation (16) using the measured data for each test condition

$$U_\infty = \frac{2\dot{q}_{fm}}{p_t} \quad (16)$$

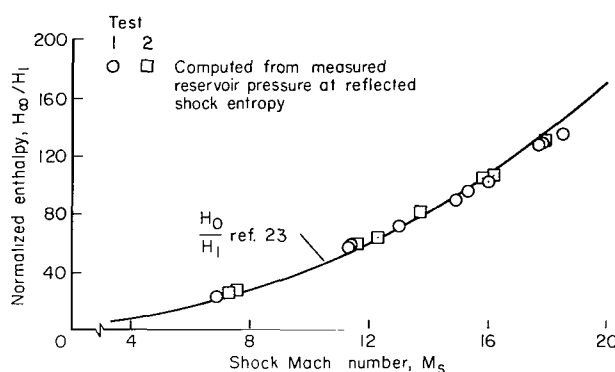


Figure 9.— Variation of total enthalpy with M_s for nitrogen.

The results of this analysis are shown in table 3, where the two sets of U_∞ are seen to be in good agreement. This finding implies that there are no significant energy losses in the reservoir for the range of conditions tested, and that the total enthalpy of the test core matches that of the reservoir.

The variation of total enthalpy with M_s is shown in figure 9. Symbols denote computed values based on the measured reservoir pressure and the entropy level associated with the reflected shock wave. Computed enthalpies are compared with a theoretical, reflected shock curve taken from reference 23; differences are due to the change of reservoir pressure after shock reflection.

Free-Stream Properties

A nonequilibrium nozzle flow program similar to that of reference 9 was used for comparing the measured flow properties with theoretical predictions. The major uncertainty involved in this program lies in the assumption that the vibrational energy mode always remains in equilibrium with translational and rotational modes. (While the energy in vibrations is at most about 20 percent of the total enthalpy, its disposition can make a noticeable difference in stream properties, as will be shown later.) The reservoir temperature and pressure are specified as initial values for the numerical solution. In the present cases the initial values were the measured reservoir pressure and the corresponding equilibrium temperature obtained from thermodynamic charts for nitrogen, using the appropriate reservoir enthalpy. Energy losses from the reservoir gas were assumed to be negligible; thus, the computed quantities represent a limiting set for the entropy associated with each test condition. The numerical computations showed that the nitrogen atom concentration was frozen in the test section for all the cases considered.

The semiempirical method of reference 6 also can be used to predict certain stream properties, without knowledge of the specific relaxation processes or rate constants. It is assumed that the gasdynamic properties at the test station (having undergone relaxation of several internal degrees of freedom) are approximately the same as if the gas had made a sudden transition from equilibrium to a zero rate of internal energy exchange at some location in the expansion. The location of the transition is characterized by a single parameter, the freeze Mach number. Downstream of this point both the chemical composition and vibrational energy distribution of the gas are constant (frozen).

A computing program for one-dimensional nozzle flow, using equilibrium reservoir conditions as input quantities, was used to generate stream properties as a function of area ratio for a specified set of freeze Mach numbers. The pitot pressure was calculated assuming the vibrational mode and chemistry remained frozen behind the bow shock wave — a realistic choice for the flow conditions of the present experiment. The details and an experimental verification of this method are given in reference 6.

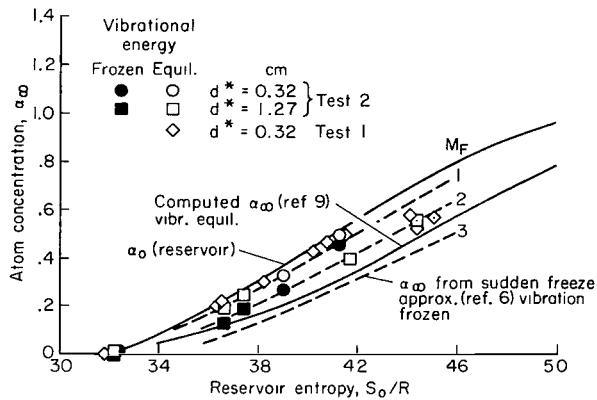


Figure 10.— Free-stream atom concentration.

The filled symbols in figure 10 represent a similar analysis in which both vibrational and chemical energy exchanges become inactive simultaneously in the nozzle expansion and remain so in the probe shock layer. Comparisons of shock-layer residence time with vibrational relaxation rates showed this a reasonable assumption except at the highest enthalpy conditions. Tables 4 and 5 summarize reservoir conditions, stream atom concentrations, and other flow quantities.

The results of figure 10 indicate that a relatively small amount of recombination occurs in the expanding nitrogen flow over most of the operating range, and that the numerical solution (with vibrational equilibrium) substantially underestimates the stream atom concentration. For frozen vibrations, the sudden-freeze approximation indicates that the internal energy adjustment stops just downstream of the nozzle throat, between $M_\infty = 1$ and 2. The effect of nozzle throat size on atom concentration appears relatively minor over the test range. At $S_0/R > 42$, recombination is enhanced and α_∞ approaches the numerical prediction.

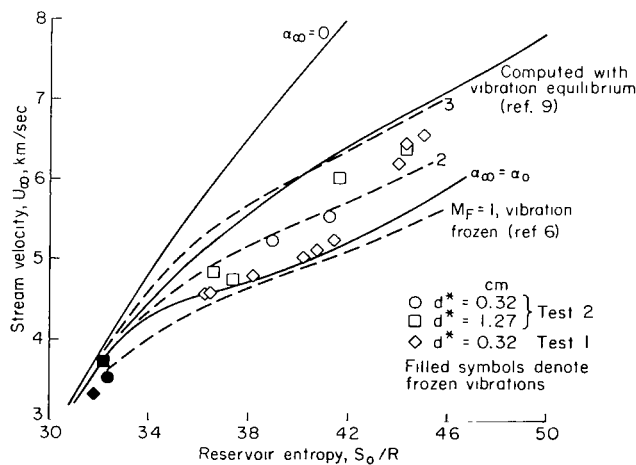


Figure 11.— Comparison of measured and predicted stream velocity.

Atom concentration— The measured and computed values of α_∞ are compared in figure 10 as a function of reservoir entropy. Reservoir atom concentration α_0 is common to both theory and experiment. The open symbols represent concentrations deduced from measured heat transfer, using equations (23) and (24) as described earlier, with vibrational energy assumed to be in equilibrium. For test 2 the probe surface was partly catalytic (copper oxide), and allowance was made for surface recombination by the method of reference 24. The recombination energy fraction varied from 4 to 26 percent of the available dissociation energy.

Velocity— Experimental and predicted free-stream velocities are compared in figure 11. The sudden-freeze predictions are shown as dashed lines, shifted downward slightly relative to the numerical solution and the α_0 curve to account for the frozen vibrational energy. The experimental values are consistent with the atom concentrations of figure 10 and, as expected, are substantially lower than the numerical prediction. At the lowest values of S_0/R the data fall below the curve for $\alpha_\infty = \alpha_0$ because of frozen vibrational energy. At the higher values of S_0/R , the velocities move toward the numerical prediction.

In the present analysis, the flow velocity was derived from experimental measurements in two ways: (1) using the stagnation heating rate

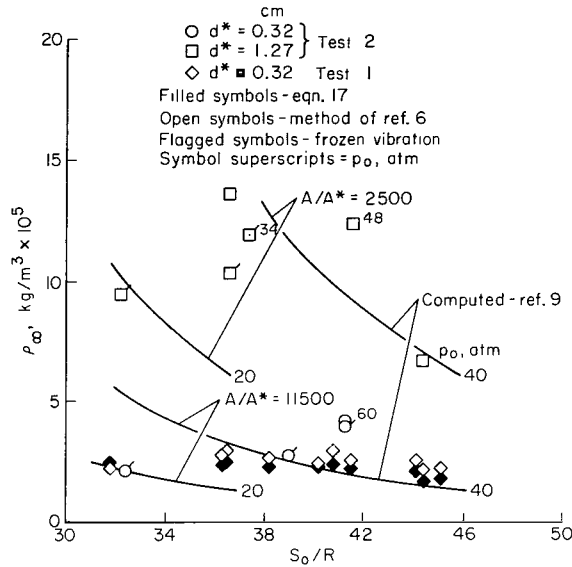


Figure 12.— Free-stream density.

experimental results agree in general with predictions on this summary plot; more exact comparisons would require a point-by-point analysis since ρ_∞ is sensitive to both reservoir pressure and local area ratio. (The area ratios shown are average values for each d^* as determined from the sudden-freeze analysis, while p_0 is within 10 percent of experiment except for the symbols with superscript values. For more detail see tables 4 and 5). The results for test 1, using the sudden-freeze analysis, compare favorably with the more direct values from equation (17). This agreement between stream densities appears to justify the assumption that the sudden-freeze analysis can be used to supplement the stream properties obtained by the three-probe method.

Shock-layer viscosity— The viscosity in the stagnation-region shock layer is obtained from the relationship of pitot pressure and heating rates given in equation (18)

$$\mu_e = \frac{d_{fr}}{4C^2} \frac{p_t^2 \dot{q}_{fr}^2}{\dot{q}_{fm}^3} \quad (18)$$

where

$$C = 0.64(j + 1)^{1/2} p_r^{-0.6} \epsilon^{-0.25}$$

The density ratio across the bow shock ϵ was evaluated using either $\gamma = (8 +)/(8 -)$ for equilibrium vibrations, or $\gamma = (4 + 3)/(4 +)$ for frozen, in the normal shock relation $\rho_\infty/\rho_e \approx (\gamma - 1)/(\gamma + 1)$ for $M_\infty \gg 1$. A Prandtl number of 0.7 was used throughout. The results are listed in table 4, where the values are seen to increase with H_0 in a regular manner. As a check on the magnitude of these values, equation (A4) of reference 24 was used to determine the shock-layer temperature T_e . Figure 13 shows that the resulting temperatures exceed the estimated values for dissociated flow with equilibrium vibrational energy; thus the measured viscosities appear consistent with the other findings of this investigation.

for a frozen shock layer, and (2) using the free-molecule heating rate as in equation (16). Comparisons are given in table 3. The first method requires a prior knowledge of the stream total enthalpy; the second does not. For this reason, the \dot{q}_{fm} method is preferable and, in fact, is a relatively simple way to determine the velocity of a nonequilibrium stream. For best accuracy, both \dot{q}_{fm} and p_t should be measured simultaneously.

Density— The computed and measured stream densities are shown in figure 12, where the filled symbols represent values from equation (17) and the open symbols are from the sudden-freeze analysis. The curves are from the exact numerical solutions (with vibrational equilibrium) at two representative nozzle area ratios A/A^* and reservoir pressures p_0 . The

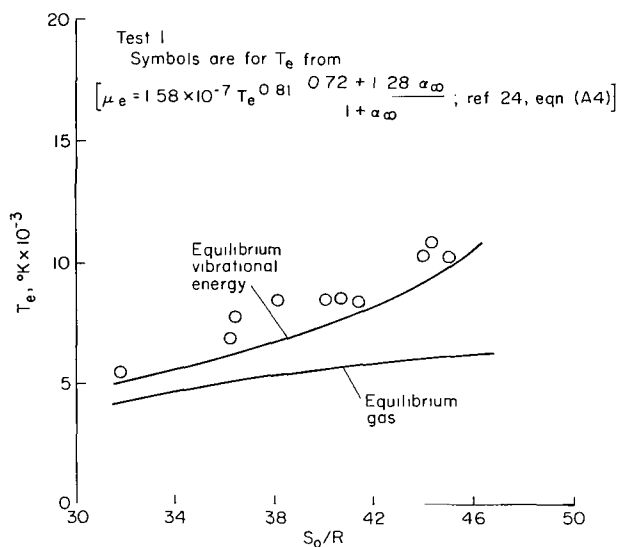


Figure 13.— Shock-layer temperature.

Shock-layer Reynolds number— Reynolds numbers in the stagnation-region shock layer were obtained from equation (14) and are listed in table 4. They remain fairly constant over the operating range, varying from 4.2 to 6.9/cm, as a result of the relatively small changes in density and viscosity observed earlier. These low Reynolds numbers reflect the high viscosities in the frozen shock layers of the present experiments.

*Mach number, Reynolds number, and A/A^** — The sudden-freeze method was used to evaluate the additional flow quantities, free-stream Mach number, Reynolds number, and effective area ratio. Results are listed in tables 4 and 5. For the smaller throat size (0.32 cm) the M_∞ increased with total enthalpy from 20 to 32 and for the 1.27-cm throat from 14 to 23. The Reynolds number did not vary in

a consistent manner with increasing enthalpy, apparently because of the increase in freeze Mach number (see fig. 11); values between 200 and 1000/cm were obtained. A substantial difference was observed, at intermediate enthalpies, between the Reynolds numbers for frozen and equilibrium vibrations (see table 5). Thus, a knowledge of the vibrational energy distribution is important in evaluating the properties of nonequilibrium streams at these energy levels.

The effective area ratio of the test stream comes directly from the sudden-freeze analysis, as shown in reference 6. The ratio A/A^* decreased with increasing reservoir enthalpy from 12,000 to about 9,000 with the small nozzle throat and from about 3,300 to 2,300 with the large throat. (The corresponding geometric area ratios are 56,000 and 3,600.) Representative boundary-layer displacement thicknesses δ^* at the nozzle exit are listed in the last column of table 5. The very substantial 20- to 23-cm thicknesses that occur with the small nozzle throat correspond to the small inviscid core size noted earlier. Obviously, for the present reservoir pressure, 0.32 cm is about the smallest throat diameter that can be used in this nozzle.

CONCLUDING REMARKS

The operating characteristics of an electric-arc-heated driver and shock-tube system, and the properties of high energy nitrogen flows expanded in a supersonic nozzle have been investigated. Driver temperatures up to 8000° K and pressures up to 340 atm were used to obtain tailored-interface conditions at shock Mach numbers from 7 to 19, enthalpies in the reflected-shock reservoir of test gas from 7 to 40 kJ/g, and test-section Mach numbers from 14 to 32. The gasdynamic processes in the shock tube and nozzle have been compared with theoretical, real-gas predictions. Local equilibrium conditions were assumed to exist everywhere in the shock tube; the nozzle flow was not so restricted, and substantial nonequilibrium effects were observed. The primary results of this investigation are summarized as follows.

1. The overall efficiency of the driver and shock-tube system was found to vary with the composition of the driver gas. Argon-helium mixtures were the most effective but did not give consistent shock-tube performance. Pure helium and pure nitrogen were less effective driver gases but produced more uniform results. Efficiencies from 40 to 100 percent were recorded.
2. An ideal, theoretical analysis of tailored-interface, shock-tube operation, which predicts a constant ratio of initial driver pressure to initial shock-tube pressure for tailoring at all shock velocities, was not confirmed by experiment. However, the nonideal effects that invalidated this prediction could be offset by increasing the pressure ratio, so that near-tailored operation was achieved for shock Mach numbers from 7 to 19.
3. Reflected shock relationships and a reservoir pressure history can be used to define reservoir conditions at total enthalpies between 7 and 40 kJ/g, if successive pressure changes are considered to be isentropic. There was no significant loss of energy from the reservoir gas during the 0.5- to 1.5-msec test period.
4. The proposed method of evaluating the properties of a nonequilibrium nozzle flow of nitrogen, using simultaneous measurements of stagnation heating rates (to noncatalytic surfaces) in three gasdynamic regimes, could not be fully utilized under current test-section conditions. Limitations on probe size prevented the attainment of an equilibrium boundary layer in the stagnation region. In future work, however, it may be possible to use a catalytic probe surface to recover the dissociation energy of the shock layer.
5. By combining elements of the three-probe diagnostic method with a sudden-freeze approximation of the flow behavior it is possible to define most of the properties needed for hypervelocity, gasdynamic studies in a nonequilibrium stream. This technique has been shown to give consistent results in a single-component gas (nitrogen) over a wide range of specific energies, with initial dissociation up to 75 percent.
6. Theoretical predictions were found to underestimate the energy retained in the inert degrees of freedom (dissociation and vibration) in a rapidly expanding stream of nitrogen. Typically, the flow departed from thermodynamic equilibrium just downstream of the nozzle throat and was effectively frozen at a local Mach number of about 2.

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TABLE 1.— RATIOS OF INITIAL DRIVER PRESSURE TO DRIVEN TUBE PRESSURE FOR TAILORED OPERATION

Driver/driven gases	He/N ₂	(0.3A + 0.7He)/N ₂	(0.4A + 0.6He)/N ₂	A/N ₂	N ₂ /N ₂
p_t/p_1	117	31.5	25.5	11.7	25.0

TABLE 2.— SHOCK TUBE, NOZZLE RESERVOIR, AND TEST STREAM QUANTITIES FOR NITROGEN

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Test	$p_1 \times 10^3$, atm	M_s	$p_{O'}$, atm	$H_{O'}$, kJ/g	d^* , cm	ζ_L $p_t \times 10^3$, atm	Theoretical \dot{q}_{eq} W/cm ²	Measured \dot{q}_{eq} W/cm ²	Local $p_t \times 10^3$, atm	Measured \dot{q}_{fr} W/cm ²	Measured \dot{q}_{fm} W/cm ²	Test interval msec	Test flow duration
1	9.22	18.5	41.1	40.6	0.32	6.94	197	127	4.97	116	161	0.5	---
			17.8	43.5		8.03	191	119	5.24	127	---	.6	---
			17.7	39.1		7.21	181	123	4.62	120	153	.5	0.5
	13.2		16.0	40.8		6.12	142	---	6.12	119	165	.4	.4
			15.3	38.8		6.18	134	74	5.37	108	131	.4	.4
			14.9	38.1		5.71	124	68	5.71	---	136	.7	---
			13.0	35.4		5.30	100	58	5.30	91	125	.6	1.2
			11.4	39.5		5.24	83	55	5.24	83	108	.9	---
			11.3	34.7		4.56	75	49	4.56	79	108	.7	---
	26.3	6.9	19.4	6.9		2.58	22	18	2.58	28	40	1.2	1.6
2	13.2	15.8	59.8	31.8		9.80	265	162				1.2	1.5
	13.2	13.7	42.5	24.4		6.73	177	111				1.2	1.7
	26.3	7.6	22.1	8.2		2.79	39	29				.9	1.3
	9.22	17.9	44.2	39.2	1.27	22.6	437	341				2.0	2.4
	13.2	16.2	47.6	31.7		36.6	475	388				1.2	2.5
		12.3	34.0	19.3		23.7	259	184				1.4	2.8
		11.6	36.7	17.9		23.1	236	185				1.4	2.2
	26.3	7.3	22.1	7.8		11.7	77	71				2.0	2.4


TABLE 3.— EVALUATION OF STREAM TOTAL ENTHALPY, TEST 1

Measured p_o , atm	Calculated H_o , kJ/g	α_o	Measured \dot{q}_{fr} , W/cm ²	Equivalent α_∞	Equivalent $(U_\infty)_{fr}$, m/sec	Measured \dot{q}_{fm} , W/cm ²	Equivalent $(U_\infty)_{fm}$, m/sec	$\frac{(U_\infty)_{fm}}{(U_\infty)_{fr}}$
41.1	40.6	0.74	127	0.57	6590	161	6430	0.977
43.5	38.7	.68	119	.58	6220	---	---	---
39.1	38.5	.69	123	.53	6480	153	6450	.996
40.8	30.6	.51	119	.50	5260	165	5310	1.008
38.8	28.8	.48	74	.47	5120	131	4800	.938
38.1	27.0	.44	68	.43	5030	136	4710	.937
35.4	21.6	.32	58	.30	4800	125	4650	.970
39.5	17.9	.22	55	.22	4590	108	4600	1.003
34.7	17.1	.20	49	.20	4560	108	4660	1.022
19.4	6.9	.02	18	0	3290	40	3160	.962

TABLE 4.— FLOW CONDITIONS AND TEST-SECTION FLOW PROPERTIES, TEST 1

M_s	p_o , atm	ξ $p_t \times 10^3$, atm	H_o , kJ/g	S_o/R	α_o	α_∞	$\rho_\infty \times 10^5$, kg/m ³	$[Re/cm]_e$	$\mu_e \times 10^6$, Nsec/m ²	Sudden freeze			
										A/A^*	M_∞	$[Re/cm]_\infty$	$\rho_\infty \times 10^5$, kg/m ³
18.5	41.1	6.94	40.6	45.1	0.74	0.57	1.78	4.49	2.61	8,900	29.8	289	2.27
17.8	43.5	8.03	38.7	44.1	.68	.58	2.10	4.98	2.61	8,600	31.8	328	2.59
17.7	39.1	7.21	38.5	44.4	.69	.53	1.74	4.17	2.70	9,000	29.3	233	2.20
16.0	40.8	6.12	30.6	41.5	.51	.50	2.25	5.54	2.19	9,700	32.2	446	2.58
15.3	38.8	6.18	28.8	40.8	.48	.47	2.40	5.68	2.20	9,500	30.1	436	2.92
14.9	38.1	5.71	27.0	40.2	.44	.43	2.29	5.32	2.15	10,000	29.4	370	2.45
13.0	35.4	5.30	21.6	38.2	.32	.30	2.33	5.71	2.03	10,300	25.0	318	2.67
11.4	39.5	5.24	17.9	36.5	.22	.22	2.51	6.30	1.85	11,800	24.5	318	2.93
11.3	34.7	4.56	17.1	36.3	.20	.20	2.23	6.30	1.64	11,800	24.0	266	2.78
6.9	19.4	2.58	6.9	31.8	.02	0	2.45	6.86	1.22	11,800	19.5	207	2.22

TABLE 5.— FLOW CONDITIONS AND TEST-SECTION FLOW PROPERTIES, TEST 2

M_s	p_o , atm	d^* , cm	$p_t \times 10^3$, atm	H_o , kJ/g	S_o/R	α_o	Theoretical E.B.L. ^a \dot{q}_{eq} , W/cm ²	Measured \dot{q} , W/cm ²	Theoretical F.B.L. ^b E.V. ^c \dot{q}_{fr} , W/cm ²	Theoretical F.B.L. ^b F.V. ^d \dot{q}_{fr} , W/cm ²	α_∞ E.V. ^c F.V. ^d	Sudden freeze approximation				
												A/A*	$[Re/cm]_\infty$	M_∞	$\rho_\infty \times 10^5$, kg/m ³	δ^* , cm
15.8	59.8	0.32	9.80	31.8	41.3	0.53	309	162	158 173	157 171	0.50 .46	8900 9600	832 640	31.5 29.6	4.19 3.94	22.9 22.4
13.7	42.5		6.74	24.4	39.0	.36	192	101	109 115	110 116	.33 .27	--- 11,000	--- 303	--- 24.0	--- 2.78	--- 21.3
7.6	22.1		2.79	8.2	32.4	.02	41.0	29.2	37.6	29.6	--- .02	--- 12,700	--- 169	--- 19.8	--- 2.10	--- 20.1
17.9	44.2		22.5	39.3	44.4	.70	574	341	330 346	---	.56 ---	3200 ---	705 ---	22.7 ---	6.75 ---	2.29 ---
16.2	47.6		36.6	31.8	41.7	.53	590	388	377 407	---	.40 ---	2250 ---	452 ---	17.5 ---	12.4 ---	8.14 ---
12.3	34.0		23.7	19.3	37.4	.26	287	184	178 193	179 192	.25 .19	--- 2400	--- 675	--- 15.7	--- 12.0	--- 7.12
11.6	36.7		23.1	17.9	36.6	.22	261	185	178 186	179 186	.19 .13	2600 2800	981 518	17.0 15.2	13.6 10.4	5.84 4.57
7.3	22.1		11.7	7.8	32.2	.02	80.6	71.1	80.6	71.0	.02 0	--- 3300	--- 453	--- 13.7	--- 9.48	--- 1.78

^aE.B.L. = equilibrium boundary layer^bF.B.L. = frozen boundary layer^cE.V. = equilibrium vibrations^dF.V. = frozen vibrations



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